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Ground Freezing Effects on Soil Erosion of Army Training Lands

Part 2: Overwinter Changes to Tracked-Vehicle Ruts, Yakima Training Center, Washington

Jonathan J. Halvorson, Donald K. McCool, Larry G. King, and Lawrence W. Gatto

July 1998

Abstract: Two areas were monitored at the Yakima Training Center (YTC) in central Washington to measure changes in M1A2 Abrams (M1) tank-rut surface geometry, and in- and out-of-rut saturated hydraulic conductivity (K_{fs}), soil penetration resistance (SPR), and bulk density over the 1995–1996 winter. Profile meter data show that rut cross-sectional profiles smoothed significantly and that turning ruts did so more than straight ruts. Rut edges were zones of erosion and sidewall bases were zones of deposition. K_{fs} values were similar in and out of ruts formed on soil with 0–5% water by volume, but were lower in ruts formed on soil with about 15% water. Mean SPR was similar in and out of ruts from 0- to 5-cm depth, increased to 2 MPa outside ruts and 4 MPa inside ruts at 10- to 15-cm depth, and decreased by 10–38% outside ruts and by 39–48% inside ruts at the 30-cm depth. Soil bulk density was similar in and out of ruts from 0- to 2.5-cm depth, and below 2.5 cm it was generally higher in ruts formed on moist soil, with highest values between 10- and 20-cm depth. Conversely, density in ruts formed on dry soil was similar to out-of-rut density at all depths. This information is important for determining impacts of tank ruts on water infiltration and soil erosion, and for modifying the Revised Universal Soil Loss Equation (RUSLE) and the Water Erosion Prediction Project (WEPP) models to more accurately predict soil losses on Army training lands.

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Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

PREFACE

This report was prepared by Dr. Jonathan J. Halvorson, Biological Systems and Engineering, Washington State University, Pullman; Dr. Donald K. McCool, U.S. Department of Agriculture–Agriculture Research Service, Pullman, Washington; Dr. Larry G. King, Washington State University, Pullman; and Lawrence W. Gatto, Geological Sciences Division, Research and Engineering Directorate, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire. Funding for this research was provided by the Office of the Chief of Engineers, CERD-M, through the 6.1 Environmental Quality Technology Program, Conservation Pillar, BT-EC-B10 Project, *Soil Erodibility and Runoff Erosivity Due to Soil Freezing and Thawing.*

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CONTENTS

ILLUSTRATIONS

Figure

TABLES

Ground Freezing Effects on Soil Erosion of Army Training Lands
Part 2 : Overwinter Changes to Tracked-Vehicle Ruts, Yakima Training Center, Washington

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INTRODUCTION

Heavy tracked vehicles create ruts, compact soils, and disturb vegetation, thereby increasing the potential for erosion. Ruts can concentrate surface water flow, depending on orientation, slope, soil characteristics and landscape position (Voorhees et al. 1979, Foltz 1993). The geometry of hillslope channels, such as rills or ruts, is important because it influences the velocity and thus erosivity of water flowing in it (Elliot and Laflen 1993, Gatto 1997b). Soil compaction affects erosion by changing the stability and size distribution of soil aggregates, and increasing soil bulk density and penetration resistance (Thurow et al. 1993, Gatto 1997b). Small increases in soil bulk density can result in disproportionately large decreases in infiltration rates that increase the potential for runoff (Meek et al. 1992). Vehicle traffic can physically disrupt vegetation (Shaw and Diersing 1990, Greene and Nichols 1996, Jones and Bagley 1997) but may also indirectly impact plant growth by altering nutrient availability, soil physical characteristics, and patterns of soil moisture storage (Wolkowski 1990, Buchkina 1997).

Wind and water erosion (with cycles of wetting and drying and freezing and thawing) modifies rut geometry and ameliorates soil compaction (Thurow et al. 1993, Gatto 1997a,b, Sharratt et al. 1997). As it thaws, frozen wet soil becomes temporarily weakened with a low resistance to erosion (Formanek et al. 1984, Kok and McCool 1990). Freeze–thaw effects may be especially important in cool semiarid locations such as the Yakima Training Center (YTC) in central Washington (Fig. 1), where the majority of precipitation occurs from late fall to early spring (Rickard 1988), coinciding with times of soil freezing. Information about how freeze–thaw cycles affect the shape and the degree of soil compaction in tank ruts is important for assessing impacts of ruts on water infiltration and soil erosion. In addition, soil erosion models such as RUSLE (USDA-NRCS 1997) and WEPP (USDA-ARS 1997) can incorporate this information to more accurately predict soil losses on Army lands in cold climates.

This research is part of a CRREL / USDA-ARS project to determine soil freeze–thaw effects on hydraulic geometry, soil strength, infiltration, runoff erosivity and soil erodibility of vehicular ruts and natural rills. Our specific goal for the 1995–1996 winter was to determine the effect of soil freeze–thaw cycles on the surface shape and compaction of M1 tank ruts. Changes in rut geometry and degree of soil compaction are important to rut-flow hydraulics and erosion, and they can be readily measured by military land managers.

RESEARCH SITES

We established two research sites 8 December 1995 within the boundaries of an ongoing Tracked Vehicle Impact Model (TVIM) study, managed by YTC personnel (Jones and Bagley 1997). We chose these sites because they represent conditions common on the YTC, were accessible, and had uniform vegetation and soil. In addition, information about the date of rut formation and antecedent soil moisture was available.*

*Russell Fitzgerald, YTC, personal communication 1997.

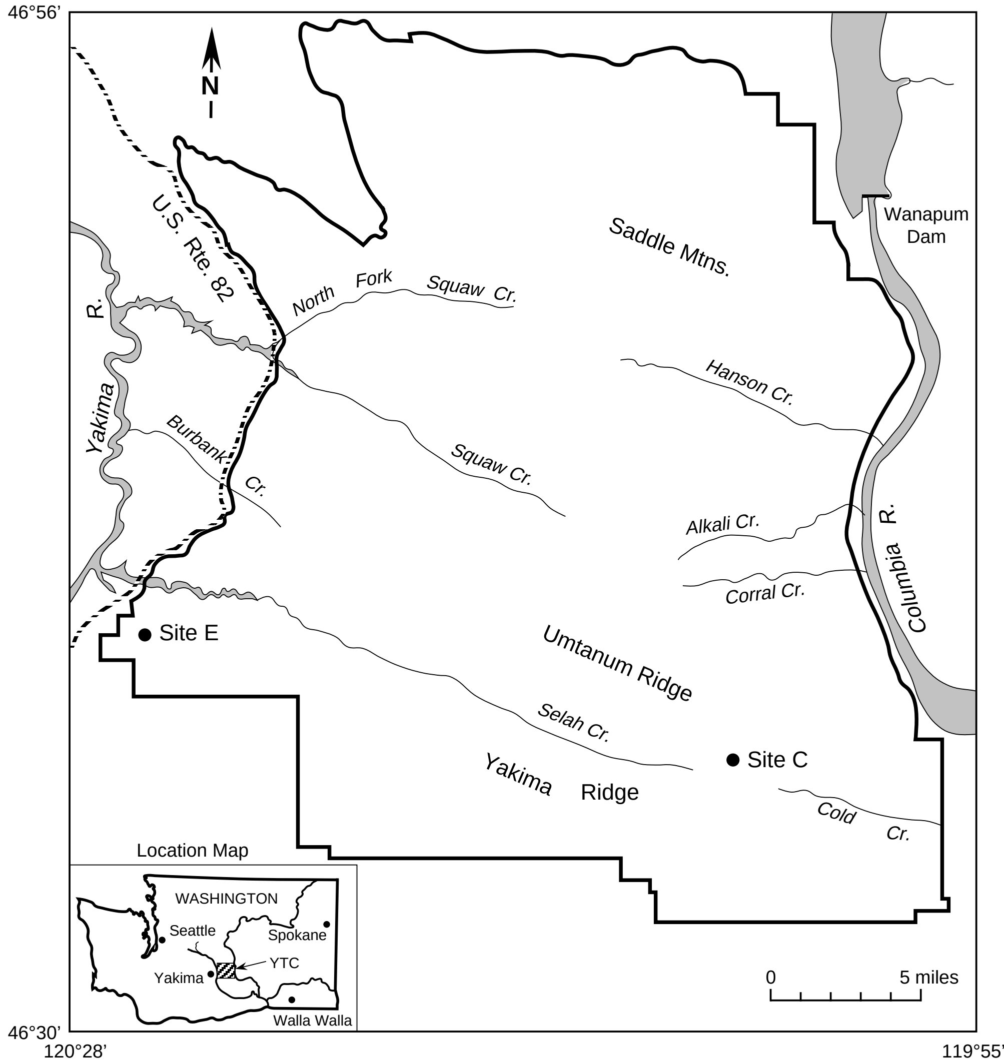

Figure 1. Research sites, Yakima Training Center.

The YTC encompasses an area over 130,000 ha in the Columbia basin of south-central Washington (Fig. 1). The region is part of the shrub-steppe, the largest of the grassland regions in North America (Rogers and Rickard 1988). Soils are typically loess overlying basalt, and the climate is characterized as semiarid, temperate, and continental with cold, wet winters and hot dry summers (Rickard 1988, Jones and Bagley 1997).

Site E (Fig. 2), at about 450-m altitude, receives about 20 cm of precipitation annually. The soils and vegetation are typical for central Washington state: shrub-steppe consisting of deep silty clay-loam soils (Drysel, Meloza-Roza; fine, montmorillonitic, mesic Xeric Camborthids) on

Figure 2. Site E.

Figure 3. Site C.

Table 1. Data on TVIM ruts that we measured.

Site	*Rut name*	*No. of passes*
C	T-2	2
	T-4	4
	TURN 1	2
	TURN 2	1
E	T-2	2
	T-8	8
	TURN 1	1
	TURN 2	1
	TURN 3	1

All ruts formed in April 1995, except E T-8 which was formed in July 1994. Soil water at time of tracking at T-8 was 0–5% (by volume); for all others it was 15%.

a 0–3% slope, and dominated by big sagebrush (*Artemisia tridentata*) (Daubenmire 1970, Jones and Bagley 1997). Site C (Fig. 3), at about 900-m altitude, has lower temperatures and about 30 cm of annual precipitation. Soils are Colockum-Benway, fine loamy, mixed, mesic Calcic and Aridic Calcic Argixerolls on a 1–3% slope. The dominant vegetation is perennial bunchgrass such as bluebunch wheatgrass (*Elytrigia spicata*) or *Poa secunda*. Further details about vegetation at both sites are reported by Jones and Bagley (1997).

Tank ruts examined during this study were formed by one to eight passes of an M1A2 Abrams combat tank in July 1994 or April 1995 as part of the TVIM study (Table 1). Jones and Bagley (1997) provide more details on site layout. The M1 has a listed vehicle weight of about 63,000 kg (69.5 tons), yielding a ground pressure of 1.08 kg/cm^2 (15.4 psi) (General Dynamics 1997). We concentrated most of our measurements on ruts formed in April 1995 when soil water content was about 15% (by volume) in the top 10 cm (moist), because we observed little surface rutting in locations where tracks were formed in July 1994 when soil water was 0–5% (dry) (see also Thurow et al. 1993).

MEASUREMENT AND ANALYTICAL METHODS

Rut profiles

We established 23 rut surface profile locations across ruts at site C and 21 at site E (Fig. 4). At site C, we measured profiles across straight ruts formed by 2 or 4 tank passes (6 replicates each) and across turning ruts formed by 1 or 2 passes (6 and 5 replicates, respectively). At site E, we measured profiles across straight ruts formed by 2 or 8 tank passes (6 replicates each) and across 3 turning ruts formed by 1 pass (9 replicates in all).

We established transects perpendicular to single tank ruts (each tank track is composed of two such ruts). We drove a 1-m length of steel rebar into the soil outside the tank rut at both ends of a profile location to serve as a stable foundation for repeated measurements with a profile meter, such as described in McCool et al. (1981) (Fig. 5).

The profile meter is composed of a 1.83-m aluminum frame that supports 145 free-sliding, vertical aluminum-alloy pins arranged in a line on 1.27-cm spacing. The frame is held perpendicular to the soil surface by folding aluminum arms that also house a camera. To measure the rut, the profile meter is placed onto the rebar, and the frame is leveled using a bubble level so that the pins point directly down. The aluminum pins are carefully lowered onto the soil surface taking care that each is in contact with the soil surface. The details of the soil surface are shown by the height of the 145 aluminum pins against a scaled backdrop on the aluminum housing frame, which is photographed (Fig. 6).

Each rut profile was photographed three times, 8 December 1995, 27 March 1996, and 16 July 1996. Each photo was digitized using SprintScan 35 (Polaroid) at a resolution of 1021 dots per inch (dpi) and archived as tagged image file format (TIF) files. Digitized images of pin heights were processed to correct for picture angle and exposure, and pin height measured using Sigmascan 3.02.035 (SPPS Inc. 1997a). We judged 46 data

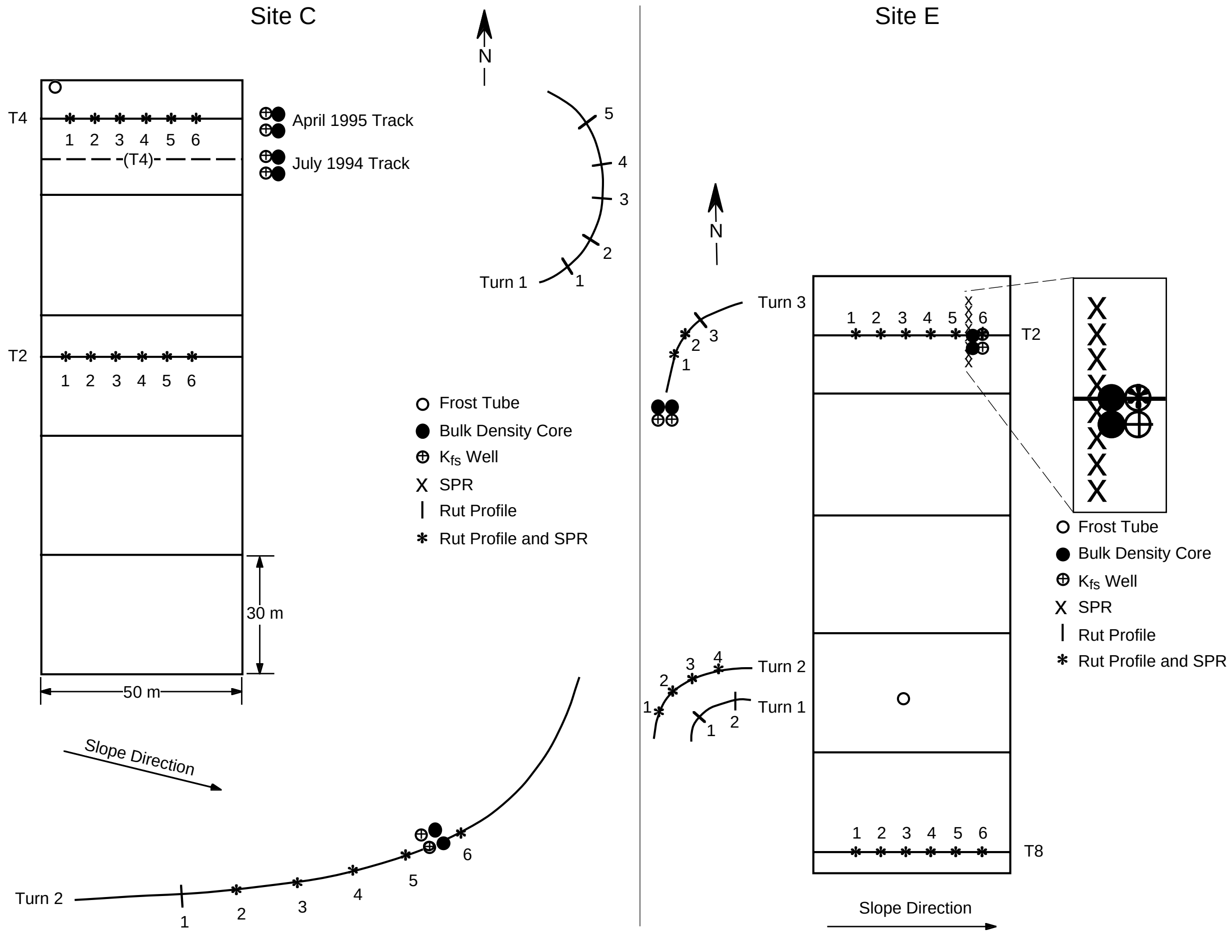

*Figure 4. Rut profile transect and soil property measurements locations; the symbol ⊕ indicates the approximate locations of Guelph permeameter wells, • are soil cores to calculate bulk density (BD), and **x** indicates permeameter locations (SPR); drawing is not to scale.*

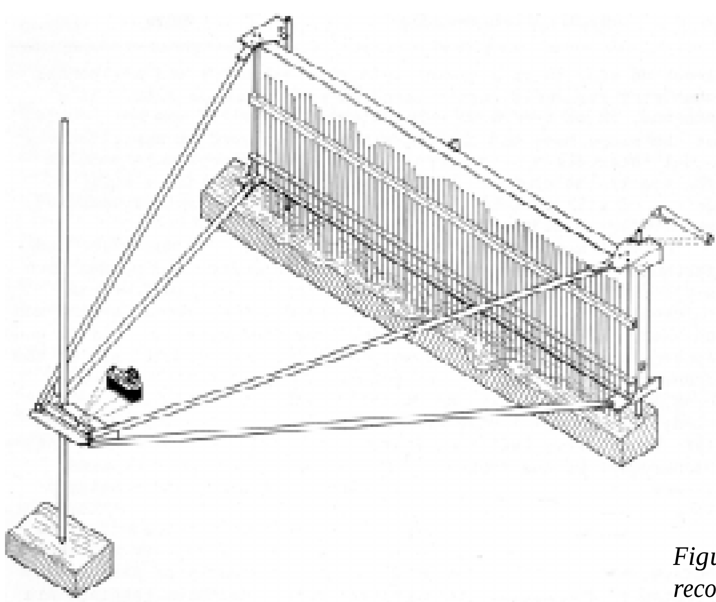

Figure 5. Schematic of a portable photographically recording profile meter (from McCool et al. 1981).

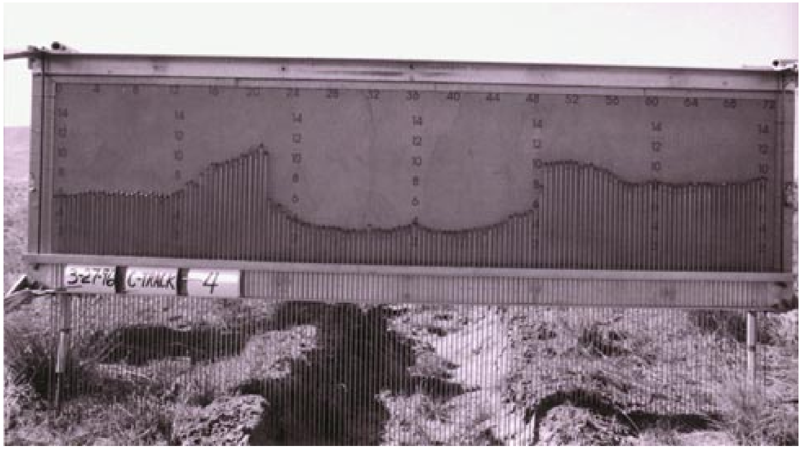

Figure 6. Details of rut surface profile measured with the profile meter.

points, out of over 20,000, as statistical outliers and excluded them from further analysis.

To determine whether significant changes in rut profiles occurred over time, we calculated the standard deviation of the 145-pin height readings of each profile for each date. We used two-way analysis of variance (ANOVA) with the December 1995 standard deviations to compare initial differences between the two sites and between straight and turning ruts. We evaluated changes in profile smoothness over time using nonparametric tests including Friedman's two-way analysis of variance, the Kruskal–Wallis test, and the Kolmogorov–Smirnov test. We selected nonparametric statistics to relax classical assumptions about spatial and temporal independence of the data and about the shape of the sample distributions. All statistics were calculated using Systat 7.01 (SPSS Inc. 1997b).

Soil properties

We measured snow depth and used a visual frost gauge (Schellekens and Williams 1993) to estimate frost depth at each site during the 1995–96 winter to establish baseline values for sites E and C (Fig. 7).

On 1–3 May 1996 we measured saturated hydraulic conductivity (K_{fs}), soil penetration resistance (SPR), and bulk density in moist and dry-track locations at both sites (Fig. 4). We sampled compacted rut soil and adjacent, uncompacted soil lying within 1 m of the center of ruts. We chose this distance because our initial measurements showed the zone impacted during tank

a. Frost gauge.

b. Reading frost guage.

Figure 7. Frost gauge and frost gauge being read. Depth of freezing is indicated by a change in color.

trafficking extending less than 1 m out from the rut, and we stayed close enough to the rut to minimize the effects of natural spatial variability within the soil. The out-of-rut measurements were always made on the "out-facing" side of a rut, and not in the "shadow" of the tank pass, to avoid bias caused by dragging of the tank undercarriage over the soil.

We measured in-situ K_{fs}, with a Guelph permeameter (Soilmoisture Equipment Corp.) to determine water infiltration into and through the soil, which would be useful for predicting rainfall infiltration and runoff (Reynolds 1993). We measured steady-state infiltration rates in

a. Soil corer.

a. Guelph permeameter.

b. Collection of soil cores.

b. Measurement well.

Figure 8. Setup of the Guelph permeameter and details of a measurement well.

c. Details of an individual core.

Figure 9. Soil corer and cores.

a. Before measurement.

b. During measurement.

Figure 10. Soil penetrometer and operator.

standard 15-cm deep wells using 5 and 10 cm of head (Fig. 8). From these rates we calculated K_{fs}, expressed in centimeters / second. We collected data in straight ruts and turning ruts at both sites (Fig. 4). Near the locations of these permeameter measurements, we also collected 5- × 2.5-cm cores of soil at different depths to determine bulk density (Fig. 9). At site C we took 12 cores, every 2.5 cm from the soil surface to 30-cm depth; at site E, 6 cores every 5 cm. These cores were returned to the lab, weighed, dried at 105°C to a constant weight, and then used to calculate soil moisture content and bulk density (dry mass per unit volume).

We measured soil penetration resistance (SPR) to assess soil strength and density inside and outside of ruts as a function of depth close to many of the profile locations (Fig. 4). We quantitatively assessed spatial variability and "edge" effects by also measuring SPR every 15 cm along a 5.8-m transect perpendicular to site E rut T-2 between rut profiles 5 and 6. We used a hand-operated cone-type Bush recording soil penetrometer (Findlay, Irvine Ltd.), which measures the amount of force required to penetrate soil (e.g., Anderson et al. 1980, Vazquez et al. 1991). The operator positioned the penetrometer perpendicular to the soil surface and pushed into the soil with a steady force (Fig. 10). We used the same operator and technique for all SPR measurements. The instrument measured SPR at 2-cm depth increments down to 30 cm and stored the information in an onboard datalogger.

RESULTS AND DISCUSSION

Frost depths

Table 2 lists snow accumulation and frost depths at various times. However, because frost depths were not read daily, these data do not show the number of freeze–thaw cycles at the two sites. The frost data indicate that the soil at site C froze deeper than that at E, although this difference diminished later in the winter; deeper frost

Table 2. Snow and frost depth.

	Snow depth (cm)		*Frost depth* (cm)*	
Date	*Site C*	*Site E*	*Site C*	*Site E*
12-11-95	6	0	0.0–18.2	0.0
12-15-95	0	0	5.5–17.5	0.0
12-19-95	3	0	0.0–3.5, 6.0–15.5	0.0–3.7
12-21.95	0	0	0.0–4.0, 5.5–13.0	0.0
12-28-95	0	2	0.0–23.0	0.0–10.0
01-02-96	0	1	1.5–26.5	0.0–9.5
01-03-96	0	0	4.0–26.0	1.5–9.0
01-04-96	0	0	0.0–2.0, 5.0–26.0	0.0–9.0
01-05-96	0	trace	0.0–26.0	0.0–1.5, 3.0–9.0
01-09-96	0	4	4.5–24.5	0–7.5
01-11-96	0	4	5.0–23.0	0–7.5
01-12-96	0	4	5.0–23.0	0–7.5
01-16-96	0	0	0.0	7.0–7.5
01-17-96	0	0	0.0–1.5	0.0
01-18-96	0	0	0.0–6.5	0.0
01-22-96	10	9	0.0–12.0	0.0–6.2
01-23-96	10	9	0.0–12.5	0.0–6.8
01-24-96	14	14	0.0–13.0	0.0–7.5
02-27-96	7	2	0.0–4.0	0.0–5.5
03-01-96	0	0	0.0–11.0	0.0–10.0

* Readings indicate the range of depths for frozen soil as recorded by a frost tube. Thus a reading of 0.0–3.7 indicates the soil was frozen from the surface to a depth of 3.7 cm. A reading of 0.0–1.5, 3.0–9.0 indicates the soil was frozen from the surface to a depth of 1.5 cm, unfrozen from 1.5 to 3.0 cm, and frozen from 3.0- to 9.0-cm depth.

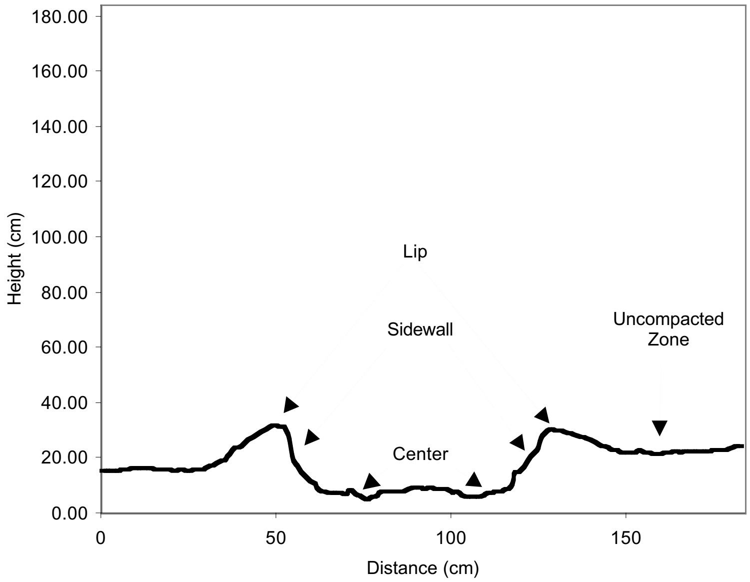

Figure 11. General cross-sectional shape of an M1 Abrams tank rut.

at site C is expected because it is cooler than site E. One implication of a deeper frost depth is that possible freeze–thaw effects can extend farther into the soil profile at site C than site E. However, changes in soil compaction and rut profile may relate more to the number of freeze–thaw cycles than the depth of freezing. Both sites had days when a thawed layer of soil was observed between two frozen layers, indicating periods of partial, shallow thawing followed by refreezing. An important implication of deeper frost at site C is that water infiltration, from melting accumulations of snow in spring, may be impeded by a subsurface lens of ice for longer time than at site E. If the soil moisture is already high in these soils, there will be increased potential for erosion from surface flow.

Rut profiles

M1 tank ruts at YTC are characterized by a depressed, compacted zone, about 64 cm wide, formed as the passing tank compresses the soil (Fig. 11). The rut depressions typically range from about 2 to 15 cm deep and often reveal the details of tank track patterns. A combination of shallow-shear failure and unconfined compaction from the track can result in relatively steep rut sidewalls, capped by a lip raised as much as 10–20 cm above the adjacent, unrutted soil. The soil surface outside this raised lip is uncompacted. Turning ruts sometimes exhibit an asymmetric profile with one lip more pronounced than the other lip (e.g., Appendix A, turn C 1-4, Appendix B, turn E 2-4).

A two-way ANOVA was used to test if there were overall profile differences between sites or between straight and turning ruts on 8 December 1995, the initial sampling date. The average combined rut-profile standard deviations, 4.16 cm at site C and 4.38 cm for E,were not significantly different from each other ($P = 0.35$). However, turning rut profiles had significantly higher average standard deviations than straight ruts at both sites ($P < 0.001$): 5.26 cm for turning ruts and 3.15 cm for straight ruts at C; 6.44 cm for turning ruts and 3.26 cm for straight ruts at E. The interaction term between site and rut type was not significant ($P = 0.52$), indicating that individual comparisons of turning ruts and straight ruts between sites did not differ from the combined analysis.

Analysis of combined data over time with the Friedman test, a nonparametric analog of a repeated-measures ANOVA, indicated average standard deviations of combined data decreased significantly during 1996 ($P < 0.001$), 4.31 cm on 8 December 1995, 4.03 cm on 27 March 1996, and 3.77 cm on 16 July 1996. However, changes in individual ruts during 1996 varied from slight (e.g., App. A, C T 4-1, App. B, ET 8-2) to significant (e.g., App. A, turn C 2-4, App. B, turn E 2-4). The Kruskal–Wallis one-way analysis of variance and the Kolmogorov–Smirnov two-sample test indicated that turning ruts changed significantly more than straight ruts ($P < 0.01$). In other words, turning ruts with the greatest amount of initial disturbance (highest average standard deviations in December 1995) had the highest decrease in standard deviation over time. Much of this initial smoothing appeared to originate from rapid erosion of thin edges of asymmetric rut lips and subsequent infilling of the compacted channels near the center of the ruts.

As suggested above, changes in profile did not occur uniformly within the same rut. In general, the greatest changes in rut surface microrelief, during 1996, occurred at the highest or lowest elevations of the rut profile (e.g., App. A, turn C 2-4). A net loss of profile height was most often measured at the rut lip. In contrast, the base of the sidewalls of the ruts were the zones of deposition or infilling. Little change was detected along the steep sidewalls. However, the profile meter records only profile changes that lie in an unobstructed vertical pin path. Careful field inspection showed that soil slumping sometimes resulted in concave or undercut rut sidewall geometry not detectable with this instrument.

Our profile measurements revealed inter- and intra-plot variability in rut shape and depth; this variability was not clearly correlated with the number of vehicle passes. Such variability suggests that rut formation is strongly influenced by soil variables and antecedent soil moisture.

Another important source of rut surface variability is related to soil surface conditions and soil moisture at the time of measurement. We collected initial readings on 8 December 1995, when soil was locally frozen and partially snow covered. Soil was near field capacity during our next readings on 27 March 1996. The third set of readings was collected on 16 July 1996 when the soil surface contained 0–5% water and shrink-swell cracks were evident. Accurate measurements require that the profile-meter support bars remain horizontally and vertically stable and that the reading pins rest exactly on the soil surface. Thus apparent changes in profile-meter measurements at a specific pin location may result from actual changes of the rut profile but will also reflect other mechanisms, such as frost heave or shrinking and swelling due to wetting-drying cycles, that shift the reference position (upright rebars). Also, the profile-meter pins may penetrate extremely dry, loose or wet soil and introduce a error into the profile readings. We observed this phenomenon in July 1996 for measurements in extremely dry soil at site E (see App. B).

Table 3. Field saturated hydraulic conductivity, K_{fs}, measured 1–3 May 1996. Locations shown in Figure 4.

*Plot**	*Out–of–rut* K_{fs} *(cm/sec)*	*In–rut* K_{fs} *(cm/sec)*
Plot C, M1, ×4, moist, straight	4.14×10^{-4}	1.52×10^{-4}
Plot C, M1, ×4, dry, straight	4.68×10^{-4}	4.04×10^{-4}
Plot C, M1, ×1, moist, turn	4.29×10^{-4}	2.22×10^{-6}
Plot E, M1, ×2, moist, straight	1.86×10^{-4}	2.09×10^{-4}
Plot E, M1, ×1, moist, turn	1.91×10^{-3}	3.79×10^{-4}

* Plot nomenclature syntax is in the form of plot, vehicle type, number of passes, antecedent soil moisture at time of tracking, and track path. Location notes refer to the map shown in Figure 4.

Saturated hydraulic conductivity, K_{fs}

Table 3 shows that soil compacted by the tank can have a reduced K_{fs} relative to the adjacent untrafficked soil. However, how much K_{fs} is reduced appears to be influenced by the amount of soil moisture at the time of tracking. For a location where tracks had been formed on moist soil at site C, the K_{fs} inside a rut was less than half that measured in adjacent uncompacted soil. Conversely, at a location where tracks had been formed on dry soil, the in-rut and out-of-rut K_{fs} was nearly identical. The K_{fs} rate measured outside a turning rut was comparable to values outside the two straight ruts, but K_{fs} was much lower inside the turning rut than in straight ruts. This suggests that the shearing and vertical forces generated during tank turning decrease the potential for subsequent water movement in the soil more than when a tank is moving straight.

Our measurements suggest K_{fs} is more spatially variable at site E than site C. The highest rate of K_{fs} (1.91×10^{-3} cm / sec) was recorded in uncompacted soil on a small ridge less than 100 m from a location, where the uncompacted value was an order of magnitude less (1.86×10^{-4} cm / sec). However, like site C, the K_{fs} observed at site E was lower inside a turning rut than out of rut. Unlike site C, little difference in K_{fs} was observed between a straight rut and adjacent uncompacted soil, suggesting tank compaction did not affect potential for water movement at this location.

Soil penetration resistance, SPR

We observed similar in-rut and out-of-rut patterns of average penetrometer readings at both sites. Average SPR was low near the surface,

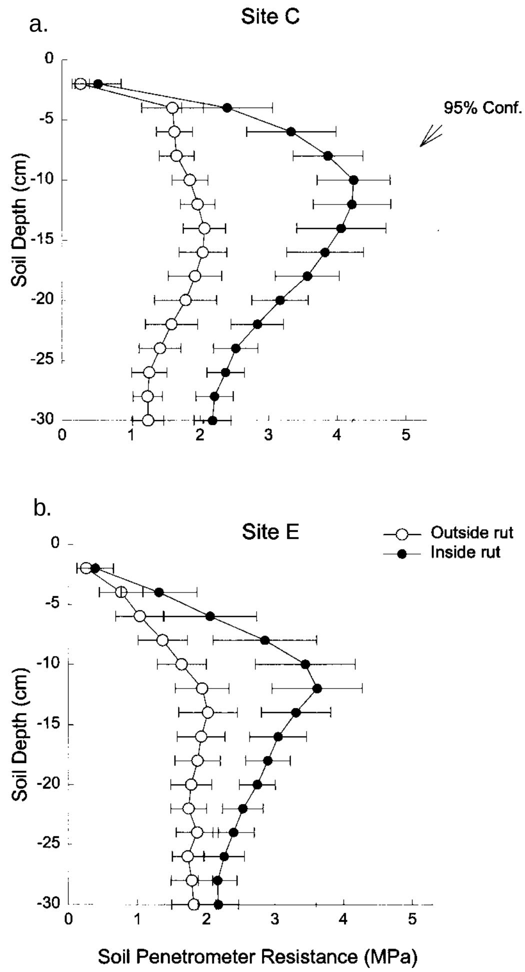

Figure 12. Average soil penetrometer resistances ±95% confidence intervals for profile locations (n = 17 [site C], 18 [site E]).

increased significantly to maximum values between 10- to 15-cm depth, and then decreased significantly with depth at site C (Fig. 12). However, at E the average SPR in unrutted soil did not decrease significantly with depth below the maximum.

More force is required to penetrate the soil in tank ruts than in adjacent uncompacted soil except near the soil surface. Average SPR was significantly greater inside ruts than outside ruts at all depths below 5 cm at site C and at depths between 7.5 and 22.5 cm at site E (Fig. 12). SPR reached a maximum average value of about 4.0 MPa inside ruts, compared to about 2.0 MPa outside the ruts at both sites. Since plant roots may have difficulty penetrating soil at SPRs greater than about 3 MPa (e.g., Taylor and Burnett 1964, Gerard et al. 1982), establishment of new seedlings in tank ruts may be impacted.

The average SPR profiles for each plot (Fig. 12) were useful for summarizing data and for statistical comparison between sites but did not reveal details about intersite variability. Some individual locations, within the sites, showed little change with depth or difference between rutted and uncompacted soil (App. D). Further, while we observed maximum average SPRs at 10–15 cm depth in both sites, turning ruts at site E exhibited simple increasing SPR with depth (App. D).

Average SPR profiles, delineated simply as inside or outside of ruts, also did not reveal details of spatial variability such as would be encountered in the field. Figure 13 shows a series of SPR profiles, measured every 15 cm across both ruts at T-2 of site E (see Fig. 4). It shows how SPR can vary greatly with small increments of depth or across short distances of the rutted landscape. The highest SPR values mark the location of the ruts where the compaction extends to 20 cm or more in depth. The uncompacted soil outside and between the ruts exhibits lower SPRs.

Bulk density

Data indicate that changes in soil bulk density due to vehicle compaction are affected by soil water content at the time of traffic and depth of measurement. Soil bulk density, both inside and outside a straight, dry soil rut at site C, were about 1.3 g cm^{-3} throughout the entire sampling depth (Fig 14a). The uncompacted soil, outside a straight rut created on moist soil, also had an average bulk density of about 1.3 g cm^{-3}, but consistently higher bulk densities were observed at all depths greater than 2.5 cm inside the rut (Fig 14b). Measurements for a single-pass turning rut, revealed a similar, though less pronounced, pattern with the greatest differences between rutted and uncompacted soil observed between 10- to 20-cm depth (Fig 14c). We observed little difference between rutted and uncompacted soil at site C near the soil surface (2.5 cm).

Average bulk density outside straight ruts at site E was about 1.1 g cm^{-3} and showed little change with depth (Fig. 14d). In comparison, bulk density inside the adjacent rut, created on moist soil, was consistently higher (about 1.4 g cm^{-3}). Bulk density was greater in a turning rut at depths above 15 cm, but it was greater in the uncompacted soil below 25-cm depth (Fig. 14e).

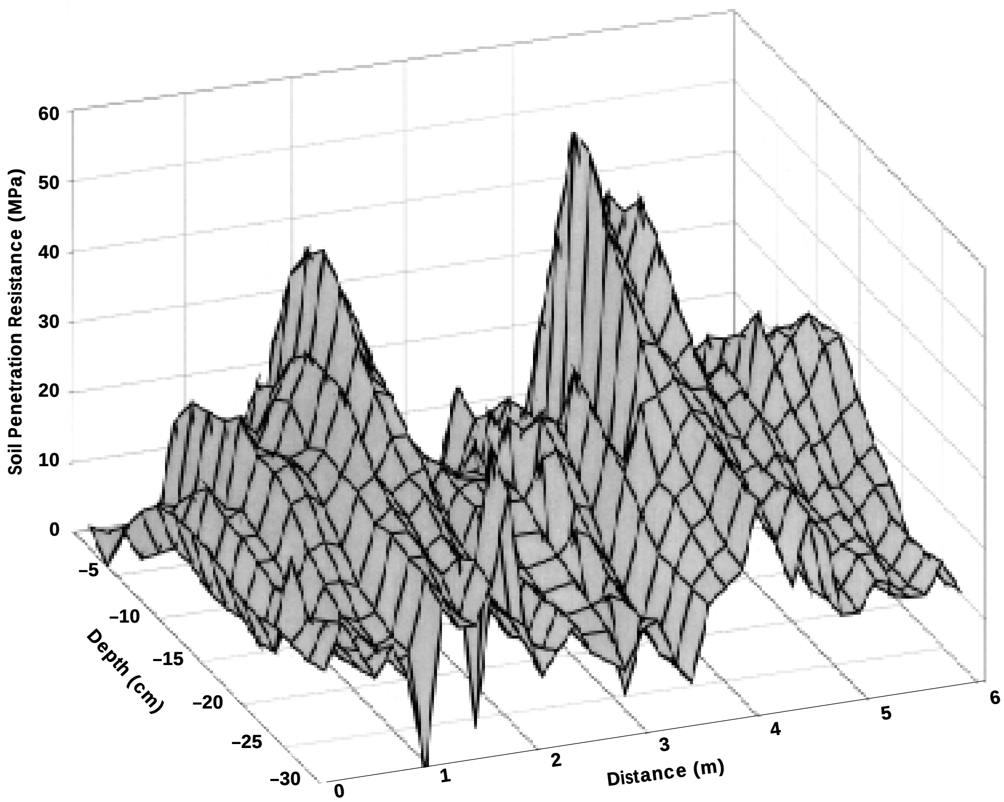

Figure 13. Response surface created from SPR transect data collected across rut T–2, site E.

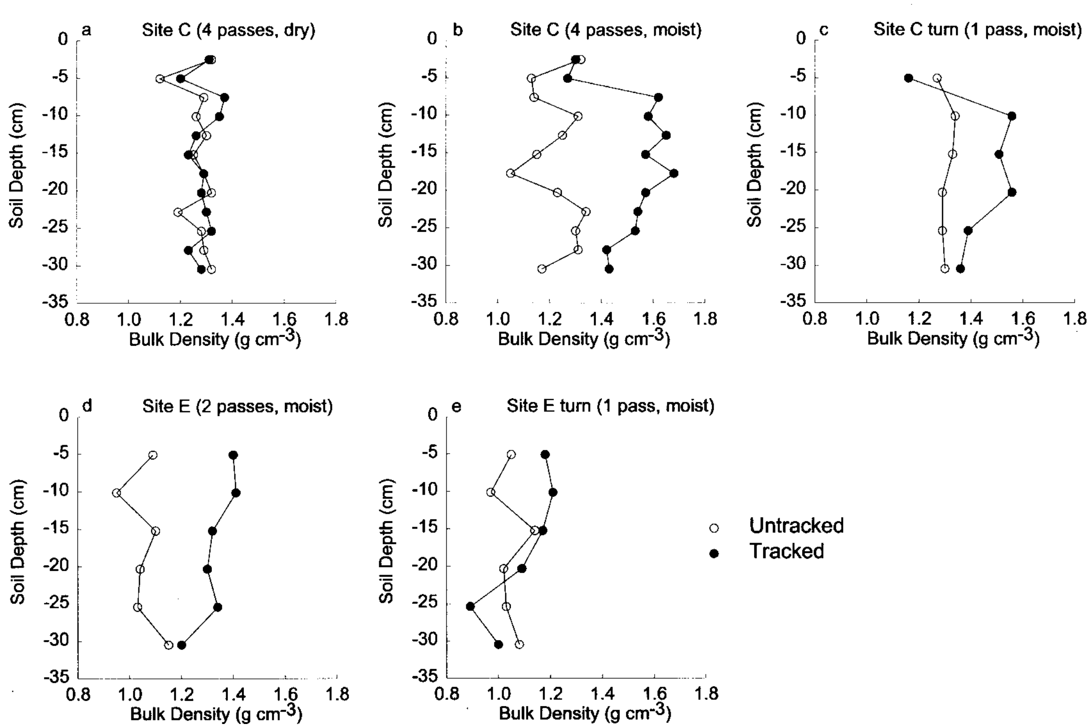

Figure 14. Bulk density as a function of depth.

CONCLUSIONS

Data collected from 8 December 1995 to 16 July 1996 document the general smoothing of tank rut geometry over the seven-month period. However, large variation in the amount of smoothing observed between individual tank ruts suggests that the initial degree of soil compaction by tanks is variable, and subsequent impacts of freeze–thaw cycles vary from rut to rut with greatest smoothing observed in deepest ruts.

The degree of compaction by tanks seems to be related to soil moisture content at the time of tracking. We observed comparatively more soil penetration resistance, higher bulk density, and lower hydraulic conductivity inside ruts at depths greater than about 2.5–5 cm when the tracks had been formed on moist soil. In contrast, we observed little difference between rutted and uncompacted soil when tracks were formed in dry soil.

Our findings also imply that soil is less compacted by tanks at the surface than deeper in the profile or that surface compaction does not persist. Less compaction may occur at the soil surface, if water content is relatively low compared to deeper in the profile at the time of tracking. Alternatively, compacted soil near the surface may be more strongly affected by forces such as wind, and wetting–drying and freeze–thaw cycles that fluctuate with higher frequency and amplitude at the soil surface.

Variation in the degree of compaction throughout the soil profile has important implications for potential erosion and its prediction, because surface conditions will not resemble the compacted soil beneath it. Site managers might underestimate environmental damage or potential erosion based on the condition of the surface soil. Alternatively, the relatively uncompacted top few centimeters may significantly offset some of the impacts of compaction on water infiltration and runoff.

FUTURE RESEARCH

Future research efforts should focus on several issues. We need to expand our basic knowledge about the particulars of soil freezing and thawing at the Yakima Training Center, including characterization of the number and degree of freeze–thaw events, the relative importance of freeze–thaw events compared to other soil modifying processes such as rainfall, and the spatial and temporal variability of freeze–thaw as affected by microclimate, landscape position, or soil depth. We also need laboratory-based experiments to provide basic information about the impacts of soil moisture on soil compaction, freeze–thaw deformation, and the effects of thawing on soil erodibility. In light of the results of this pilot study, future work at the YTC should be directed towards testing the hypothesis that amelioration of compacted soil in ruts occurs at different rates in the soil profile and its corollary that the rates of soil change are not linear.

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13. ABSTRACT (*Maximum 200 words*)

Two areas were monitored at the Yakima Training Center (YTC) in central Washington to measure changes in M1A2 Abrams (M1) tank-rut surface geometry, and in- and out-of-rut saturated hydraulic conductivity (K_{fs}), soil penetration resistance (SPR), and bulk density over the 1995–1996 winter. Profile meter data show that rut cross-sectional profiles smoothed significantly and that turning ruts did so more than straight ruts. Rut edges were zones of erosion and sidewall bases were zones of deposition. K_{fs} values were similar in and out of ruts formed on soil with 0–5% water by volume, but were lower in ruts formed on soil with about 15% water. Mean SPR was similar in and out of ruts from 0- to 5-cm depth, increased to 2 MPa outside ruts and 4 MPa inside ruts at 10- to 15-cm depth, and decreased by 10–38% outside ruts and by 39–48% inside ruts at the 30-cm depth. Soil bulk density was similar in and out of ruts from 0- to 2.5-cm depth, and below 2.5 cm it was generally higher in ruts formed on moist soil, with highest values between 10- and 20-cm depth. Conversely, density in ruts formed on dry soil was similar to out-of-rut density at all depths. This information is important for determining impacts of tank ruts on water infiltration and soil erosion, and for modifying the Revised Universal Soil Loss Equation (RUSLE) and the Water Erosion Prediction Project (WEPP) models to more accurately predict soil losses on Army training lands.

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Freeze-thaw	Tank-rut surface geometry	Yakima Training Center

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